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Blockchain-Based Energy Trading in Electric Vehicle Enabled Microgrids

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Abstract—This article presents a blockchain-based scheme for energy trading between electric vehicles (prosumers) and critical load (consumer) in a microgrid. Unlike traditional wholesale energy markets where retailers sell energy to consumers, our proposed model directly connects prosumers with consumers to meet temporary energy demands. We exploit blockchain technology to establish a trusted energy trading ecosystem. The article provides an overview of the blockchain enabled architecture that facilitates peer-to-peer energy trade in a logical network, using the building blocks provided by 5G network. An energy trading prototype is developed to remotely monitor energy trading activities between prosumers and consumer, using graphical user interface. Experimental results based on a real map of Paisley illustrate that the energy trading system is effective in finding, associating and routing prosumers to consumers, while protecting privacy of entities. Numerical results show a favorable performance of our optimization model in comparison to traditional frameworks.

I. INTRODUCTION

Domestic energy production in the UK is not sufficient to address peak demands, with 7.2% of electricity supplied from net imports in the second quarter of 2019 [1]. With the rising penetration of electric vehicles (EVs), domestic energy production will struggle to satisfy the ever-increasing energy demand. Vehicle-to-grid (V2G) offers a promising alternative to address demand-supply mismatch [2]. Additionally, EVs can also be deployed to meet the temporary demands of critical loads such as pop-up hospitals built during the Covid-19 pandemic, which may not be met by regular supply [3]. A

major challenge is the wholesale energy distribution in traditional energy markets, where energy is sold to consumers by retailers. These retailers own a tiny percentage of the grid infrastructure and only manage services such as usage metering and billing. Supplementing retailers and connecting trading entities directly unlocks a more efficient and competitive energy market. However, this transition would need a robust platform that enables increased distributed influence and provides a trusted environment for energy trading.

Blockchain is an emerging technology in which the aforementioned platform could be based [4]. First developed as the backbone technology behind Bitcoin [5], it has since grown to become a multipurpose technology for a variety of applications, including peer-to-peer (P2P) energy trading. Blockchain-enabled programs can create a trusted environment for trade between different entities [6]. For example, consortium Blockchain has been exploited in [7] to achieve trusted energy trading between EVs. A blockchain-based scheme for demand response management is proposed in [8], to facilitate energy trading between a static entity and EVs. Moving one step further, we present a prototype capable of remotely monitoring energy trading activities in EV-enabled microgrids.

As the main contributions of this work, we propose a blockchain-enabled architecture to facilitate energy trading between EVs (prosumers) and critical load (consumer) in a microgrid. The functional components that enable P2P energy trade in a logical network are analyzed. We develop an energy trading prototype to remotely monitor

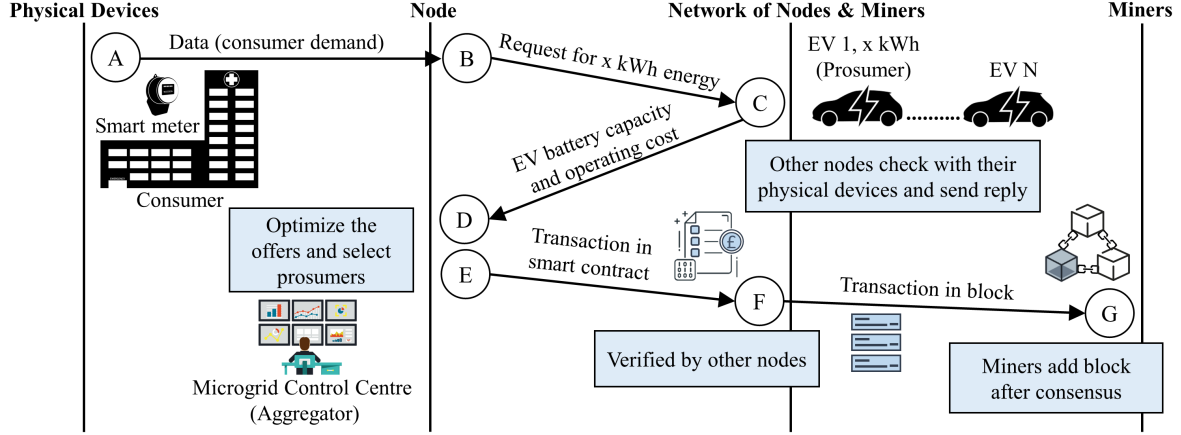


Fig. 1: Interactions between various stakeholders in the P2P energy trading network.

energy trading activities between trading entities, using graphical user interface (GUI). Based on the electric vehicle as a service (EVaaS) framework in [3], the model selects optimum prosumers to fulfill consumer demand.

II. EVAAS ENERGY TRADING SYSTEM

EVaaS describes a system where EVs communicate with the microgrid to participate in demand response services and are associated with the CL directly. In this section, we will describe our proposed blockchain-based energy trading system and clarify some myths on the use of blockchain in this area. We present the blockchain architecture as it applies to our proposed system. A more detailed study on blockchain and its various applications can be found in [9], [10].

A. Blockchain-Based Energy Trading Platform

Blockchain is an immutable distributed database made of blocks where each block is made of transactions and the hash of previous block. In the energy trading prototype, the transactions are the amount of transferred energy and the price paid for it. Each transaction will be broadcasted, and then added to the block after being validated. This way, the participants are not able to double-spend their money or double-sell their energy. The block will be added to the blockchain after a consensus among the miners. Miners are normally powerful computers hosted by the stake holders. Blockchains can be public, private or hybrid. We also have consortium

blockchains, which are considered a sub-category of private blockchains. In this article, we propose a private blockchain-based energy trading platform. In Fig. 1, we present the players in this platform and the data/message exchange among them. In addition to physical devices like smart meters that provide information about the energy level and raw data, our proposed platform has three types of blockchain nodes.

1) *Light nodes*: Blockchain nodes that have limited storage and processing power are called light nodes. In our model, EVs are examples of light nodes. These nodes can initiate transactions, but due to their limited data storage they cannot store the whole blockchain and therefore they are not able to verify transactions. Moreover, light nodes, are not able to add blocks to blockchain because this task requires complex and energy hungry computations.

2) *Full nodes*: The nodes that have sufficient storage to store the entire blockchain are called full nodes. In our model, smart homes with high capacity data drives connected to the network, or microgrid control centre (MGCC) are examples of full nodes. These nodes can initiate transactions, and verify other transactions. We assume the MGCC is a full node in our proposed platform, thus taking up the responsibility of verifying transactions.

3) *Miners/validators*: In *public Blockchains* adding blocks to a Blockchain will be done by nodes that are called miners. Miners do not need to store the entire Blockchain. However, miners with

high volume of data storage can store the entire Blockchain and become full nodes too. Similarly, full nodes with high computational power can act as miners too. In *private Blockchains* like our proposed platform, proof of work algorithms are not used and therefore miners become validators. These validators run algorithms like Practical Byzantine Fault Tolerance or Federated Byzantine Agreement which require much less processing power. In our platform, MGCCs are the validators and responsible for adding blocks.

B. Peer-to-peer Network

Blockchain works on a P2P network basis; however, it is a logical network and it does not mean that the nodes need to have direct physical connection links with each other. This logical networks needs to be supported by a reliable and fast communication network, which we later discuss in Section IV. Moreover, it is considered that the transaction is P2P without intervention of any central body. However, the transaction must be verified by other peers to be inserted in a block and the block will be added to Blockchain. Thus, there are more entities active in this procedure than the two parties at sides of the transaction. It must be noted that Blockchain service is not free and the miners/validators will be paid for the service they provide. Therefore, each transaction that is made has a cost for consumer and prosumer. This is the reason that the common myth on eliminating the middle man makes the transaction *free of charge* is not true.

C. Energy Trading Mechanism

For simplicity, we choose a centralized optimization mechanism which is performed by an entity called aggregator. Based on the mathematical framework in [3], the aggregator tries to associate optimum prosumers with consumer such that minimal operating costs are realized, while satisfying consumer energy demand and charging station constraints. The operating cost here is the sum of the energy, transportation and (Blockchain) transaction costs. The energy cost is determined by the energy volume and energy tariff. The transportation cost is determined by the distance between consumer and prosumers and the transportation tariff. Transaction

cost is fixed depending on the reward that is paid to full nodes for verifying the transactions and miners for adding a block to the chain. A detailed formulation of the optimization mechanism can be found in [3].

It is to be noted that we choose the central optimization for implementation simplicity and efficiency. In a more general framework, the optimization can be done locally at consumers, or in an auction-based model where prosumers submit their prices and time-to-deliver to the consumer as bid packages. In such scenarios, the consumer selects the best bid package based on its energy demands and cost.

III. EVAAS ENERGY TRADING PROTOTYPE

A. Prototype Development

EVaaS energy trading prototype is an application that makes use of GUI for remote monitoring of energy trading activities between prosumers and consumers. It is designed according to the energy trading mechanism introduced in Section II. A variety of tools have been selected for the prototype development which is influenced by various factors such as target operation system platform, integrated development environment (IDE), programming language and required functionalities [11]. Android Studio SDK, Java and Firebase were the selected IDE, programming language and database respectively. We have used several application programming interfaces (APIs) in the prototype development including Google Maps, Google Directions, Google Places Autocomplete and GeoFire.

B. Energy Trading Process

1) *Mode Selection:* Key players remotely access the application server to select between consumer and prosumer modes. Consumers will be able to specify energy demand and location, while prosumers will be able to set their available energy, operating costs and location. Firebase authentication services is utilized to create new user account and authenticate existing user accounts.

2) *Peer-Discovery and Optimization:* Consumers initiate energy trade request. The aggregator discovers the identities and information about energy availability of prosumers within

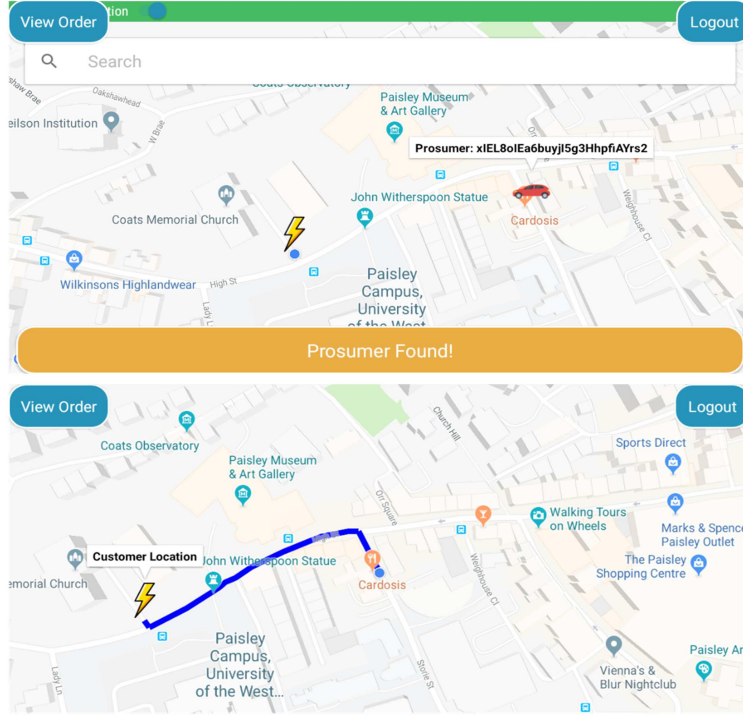


Fig. 2: Consumer (up) and prosumer (down) activity pages based on the real map of Paisley.

proximity. The varied energy and transportation costs from prosumers are optimized. The optimum prosumers are selected and presented to the consumer for confirmation. Conditions for energy trade, which includes amount of energy to be transferred and price to be paid, are entered and after simple preprocessing (availability of the funds in consumer's account and energy in prosumer's battery), a transaction will be generated. The transaction will then be sent to the private blockchain and will be processed as explained before.

3) *Energy Transfer and Payment*: Once an agreement has been reached between prosumers and consumers, the agreed price will be locked on the consumer's account. After the agreed amount of energy has been transferred in accordance with the transaction, prosumer receives payment in cryptocurrency. Being a private Blockchain, our proposed framework does not introduce a new cryptocurrency, and is flexible in using any cryptocurrency like Ether (ETH) with market value. The process is recorded to the Blockchain and it is validated across the network. Throughout the process, random pseudonyms are assigned to prosumers

and consumers to preserve privacy. The barter of energy is achieved without leaking any personal information about the entities.

C. Optimization Algorithm

We present a greedy algorithm (GA) that is designed to solve the optimization problem. The algorithm starts by computing the number of prosumers and consumers, and their distribution in a specified region. A snapshot of prosumers and consumers is obtained providing their respective positions which is used to compute the distance of the prosumers from consumers. The battery capacity of prosumers and demand of the consumers is also obtained. Out of the list of consumer to prosumer links, the link that provides the minimal operating cost is chosen, considering constraints verification. A detailed explanation of the optimization algorithm is provided in [3].

We introduce two optimization schemes which will be used later to study the performance of our proposed algorithm. In the first, the aggregator sorts the costs in non-descending order and associates prosumers using knapsack algorithm (KPA) [12].

In the second, the aggregator sorts the distances between consumer and prosumers in non-descending order and associates prosumers that are closer to the consumer using first-come first-served (FCFS) scheme.

D. Prototype Verification and Evaluation

The prototype depends heavily on leveraging the database to provide users with a real-time environment required for energy trade. When requesting for energy, consumers can either use their current location or the search text box which returns place predictions as users type. As soon as prosumers log into the system, their location and available energy are sent and stored in the database. The prototype uses information of the consumer and available (logged in) prosumers to run the optimization. It is to be noted that the application database is different from the Blockchain. This database is kept at the aggregator and prosumers or consumers do not have access to it. Fig. 2 presents the consumer and prosumer activity pages for the prototype based on a real map of Paisley. From the consumer activity page, location of associated prosumers can be monitored on the map and prosumers are assigned random pseudonyms to protect their privacy. Similarly, from the prosumer activity page, the best route to the consumer is displayed to prosumers. Once the agreed amount of energy has been transferred, the prosumer receives payment as discussed earlier. When prosumers logout of the application, their information is removed from the database.

Java MessageDigest has been used to generate a unique hash for blocks by providing details (list of transactions and time stamp) of the previous block. These values are used to generate a hash for that block, so any changes in any of these fields will alter the hash of the block. This validates the blocks in blockchain and prevents records tampering. These blocks are then added to the blockchain. Users can download the updated blockchain on their devices.

E. Numerical Results

We consider a microgrid which consists of 20 prosumers and a consumer distributed within a 4 km \times 4 km area. Energy demand between 40-200

kWh is uniformly allocated to the consumer, while energy capacity between 15-38 kWh is randomly assigned to prosumers. Energy and transportation tariffs between 0.08-0.46 cryptocurrency/kWh and 0.12-0.25 cryptocurrency/km, respectively, are randomly assigned to prosumers. We have assumed energy and transportation tariffs for simulation purposes. We have also assumed the transaction cost to be fixed, hence it is negligible in the optimization model. Considering the energy demand and coordinate of consumer, energy and transportation tariffs, available energy and coordinates of prosumers, the parameters for prosumer-consumer association are calculated. Finally, the necessary parameters are passed to the optimisation algorithms to find the best association between consumer and prosumers.

We compare the performance of our optimisation algorithm with the traditional mechanisms introduced earlier. Based on the algorithms, association has been derived for different consumer demand. We considered different scenarios for energy trading, and for each scenario, the above parameters are used to compute the total operating cost. The numerical results in Fig. 3 show that our algorithm (GA) outperforms KPA and FCFS scheme. Fig. 3a shows the operating cost of associated prosumers for different consumer demand, while Fig. 3b shows the number of prosumers associated by the different algorithms. As the energy demand of the consumer increases, so does the number of associated prosumers. However, GA associates fewer prosumers than FCFS scheme and KPA in all scenarios, thus achieving better battery capacity utilization of prosumers. The GA produces an 19% and 32% reduction in operating costs for a consumer demand of 40 kWh compared to KPA and FCFS scheme, respectively, as shown in Fig. 3a. Similarly, GA reduces operating costs by 14% and 22% for a consumer demand of 120 kWh compared to KPA and FCFS scheme, respectively. Prosumer-consumer association by GA reduces cost in every scenario by at least 4%. Overall, we can observe that our optimisation algorithm achieves reduced operating costs and better system efficiency.

IV. ENABLERS AND FUTURE TRENDS

In this section, we discuss how future enabling technologies can support the operation of EV-

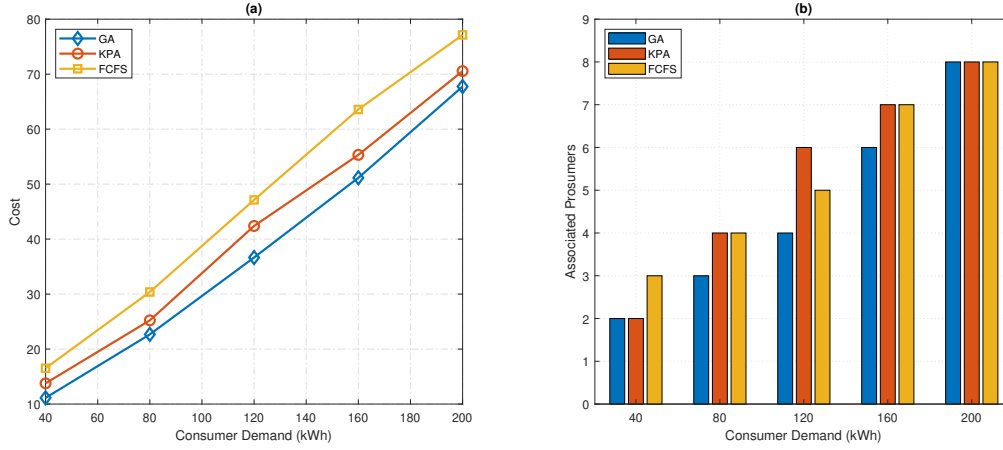


Fig. 3: Costs and associated prosumers for consumer demand in different scenarios.

enabled microgrids, as well as outline the research trends and challenges associated with the proposed architecture.

A key enabling technology required for the operation of our proposed system are 5G networks. Future communications envisage a plethora of wireless and connected smart devices that will communicate in real time while featuring different network requirements [13]. Our system is no exception; The 5G network is expected to address our system's requirements on demand, by adapting to the conditions which allows it to work on a P2P network basis implementing a logical network. Our system will take advantage of the 5G architecture which according to [14], will offer high average speeds, capacity, low latency, etc. Furthermore, the infrastructure provider can provide the infrastructure as a service (IaaS) to mobile virtual network operators (MVNOs) who may not have their own infrastructure and/or wireless network resources. In this case, the MVNO could be a niche virtual operator for the Blockchain-based energy trading in EV enabled microgrids to address the communication requirements of the proposed system.

Another enabling technology required for the proposed architecture is the advanced meter infrastructure (AMI). Through 5G networks, it is possible to support the operation of an AMI for EV-enabled microgrid. Such a microgrid is required to implement demand response mechanisms. Our system requires AMI to provide real-time energy consumption measurements of consumers. Undoubt-

edly, AMI will be a key enabler to the energy trading ecosystem if the expected functionalities are realized.

Another important enabler that needs to be considered is the legal framework that is required for the operation of the proposed service. It is therefore, necessary that a Policy and Regulatory framework for EV-enabled Microgrid applies. According to regulations in the UK and some other countries, electricity generated by individuals or businesses can only be used on site or sold directly to the utility grid for a nominal price. This poses a significant limitation to our proposed system. The authorization of P2P commerce will enable trading entities to interact directly. The proposed system may form the basis for a new techno-economic assessment and revaluation of the current legal framework.

Finally, safety is another critical topic that must be addressed in order to enable decentralized energy trading. Risk assessment of the electrical energy transfer and the definition of the dangers associated with this must be identified. This can be achieved by utilizing newly developed, as well as current safety requirements/standards [15] after they have been revisited. Potential risks can be general hazards such as exposed/loose electrical wiring, production of chemical leakages and as a result the cause of fire or explosion and possible escape of non-flammable gases when charging or discharging lithium batteries. The transferring of electrical energy can pose some dangers, nevertheless battery storage is safe if it is used properly and is well looked after.

V. CONCLUSIONS

This article has presented an energy trading system where prosumers and consumers trade energy with respect to demand-supply mismatch. Blockchain technology has been exploited to establish a trusted environment for energy trading and develop a prototype which associates prosumers with consumers directly. A greedy algorithm is presented to minimize operating cost of associated prosumers. Experimental results based on a real map demonstrate the effectiveness of the trusted energy trading prototype and numerical results show that our trading scheme achieves lower energy costs and better battery capacity utilization of prosumers.

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